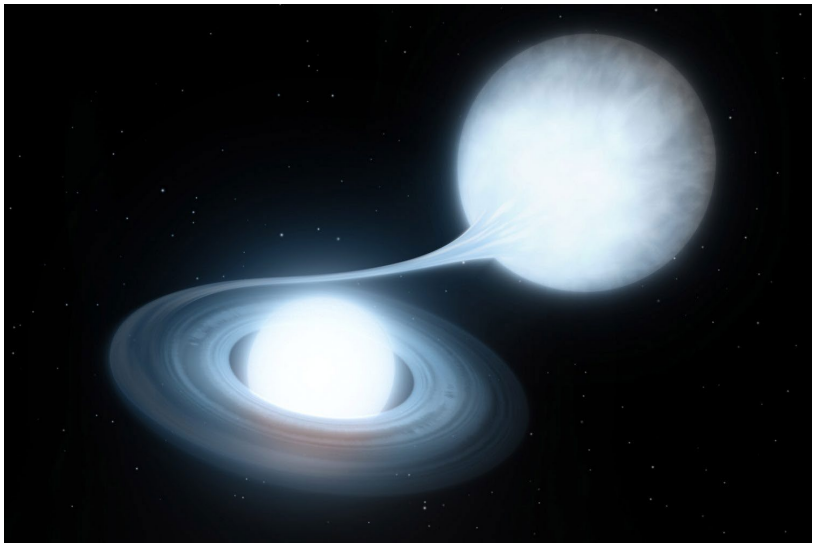
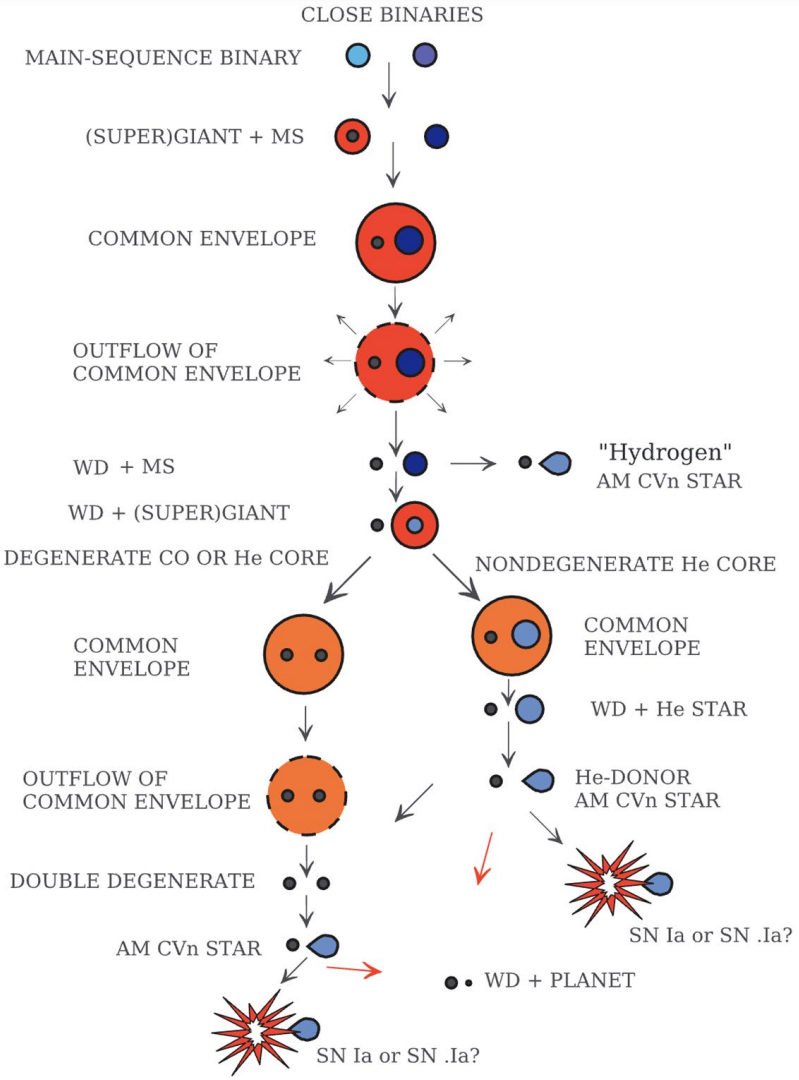
Gravitational wave-driven mass transfer in the shortest-period binaries

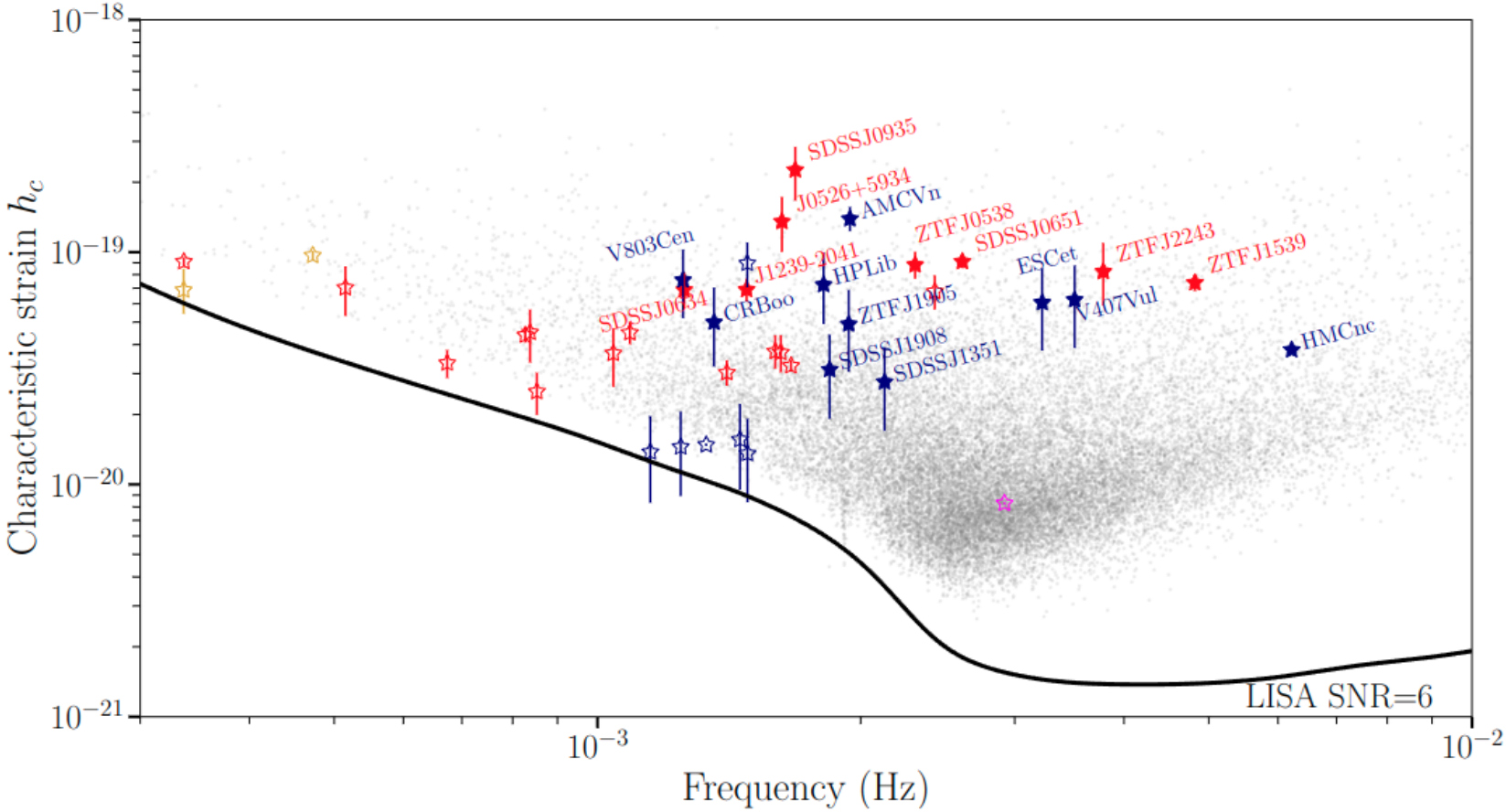


arXiv:2411.12796
ApJ, 977, 2 (Dec. 2024)

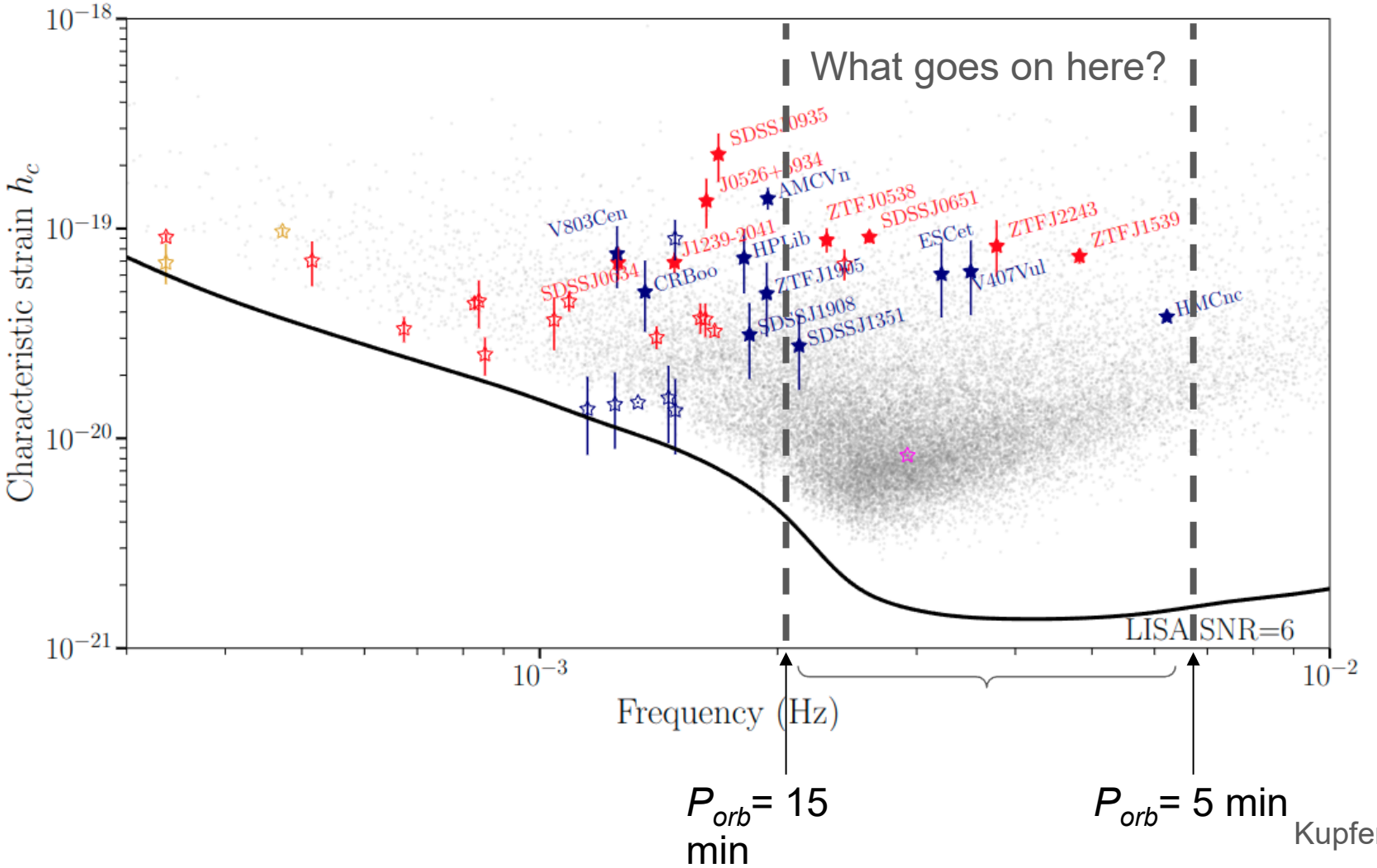
Joheen Chakraborty (MIT)
w/ **Kevin Burdge**, Saul Rappaport, Scott Hughes, Erin Kara, Emma Chickles (MIT), James Munday (Warwick), Hai-Liang Chen (Yunnan), Pablo Rodriguez-Gil (IAC), Vik Dhillon (Sheffield), ZTF Team (Caltech, ++), and others!

Binary stellar evolution: the standard picture

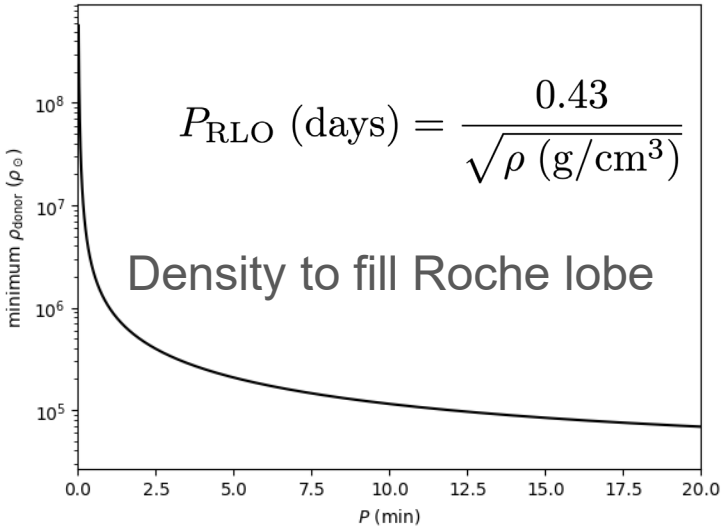




Kupfer, Korol+24

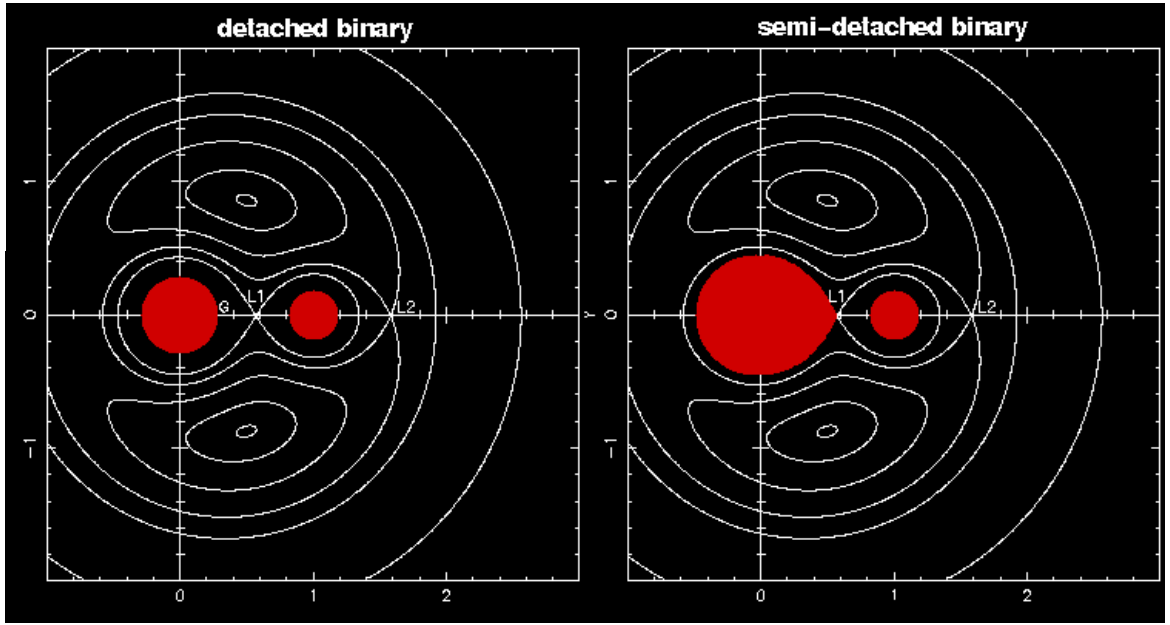


Kupfer, Korol+24



(Eggleton 1983)

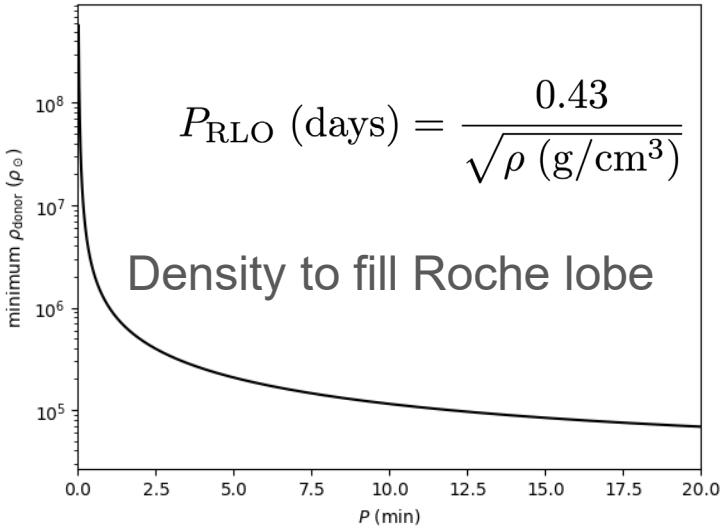
Decreasing $\rho_{\rm donor}$ →

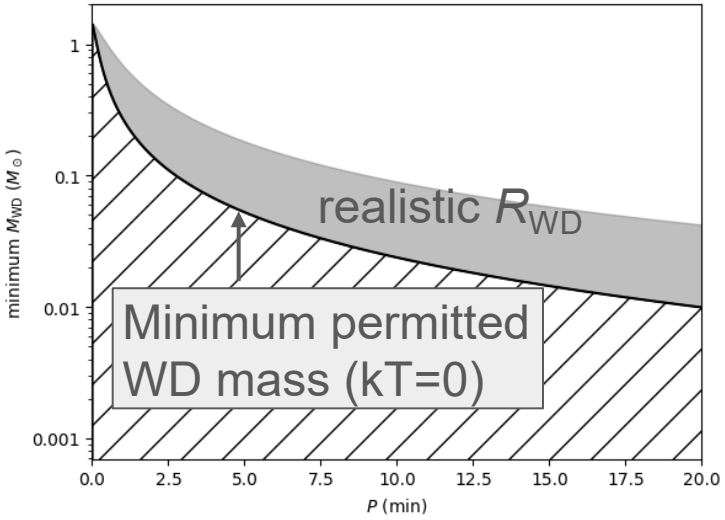


(Eggleton 1983)

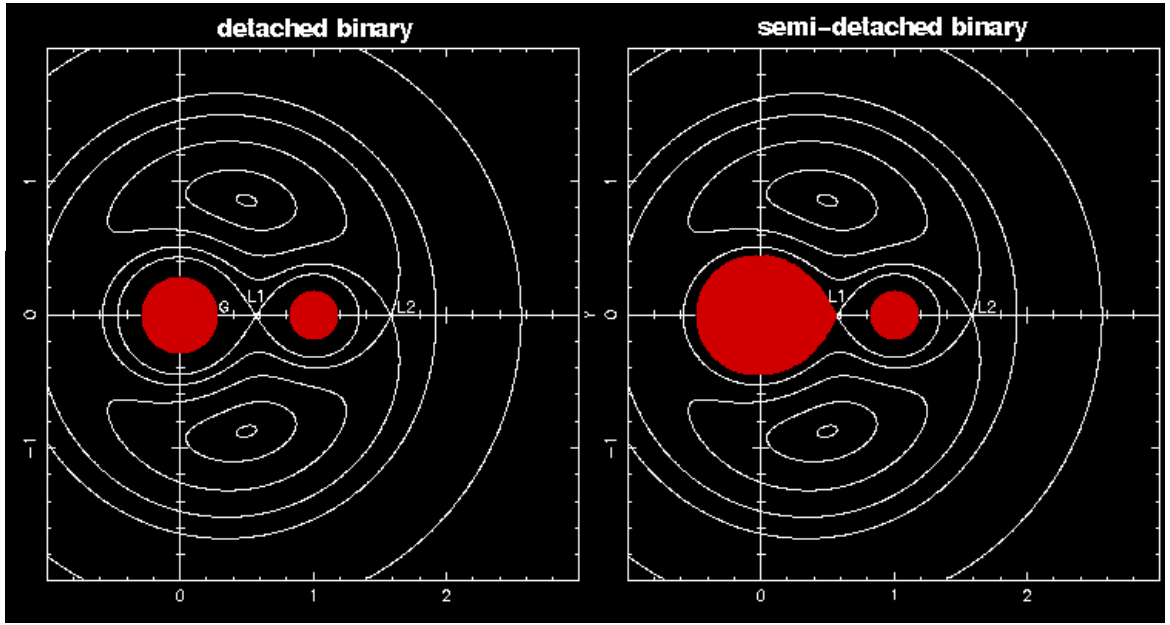
$$P_{\rm RLO}\ ({\rm days}) = \frac{0.43}{\sqrt{\rho\ ({\rm g/cm^3})}}$$

Density to fill Roche lobe



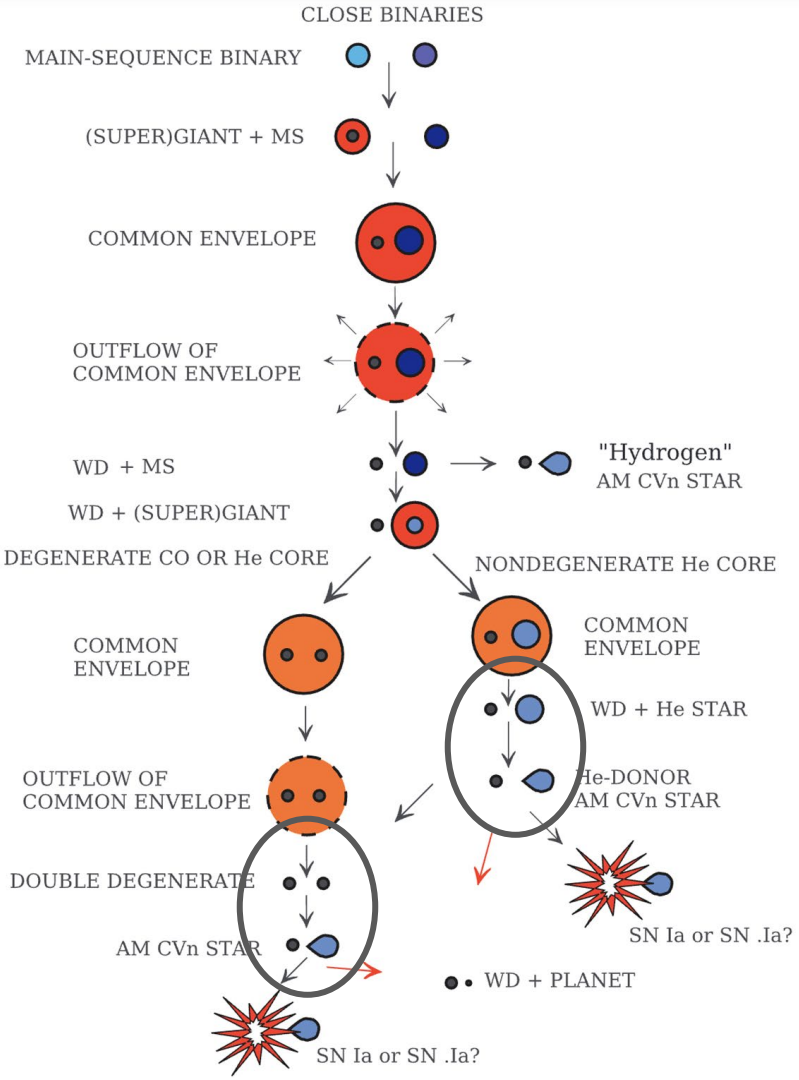


Decreasing ρ_{donor} →

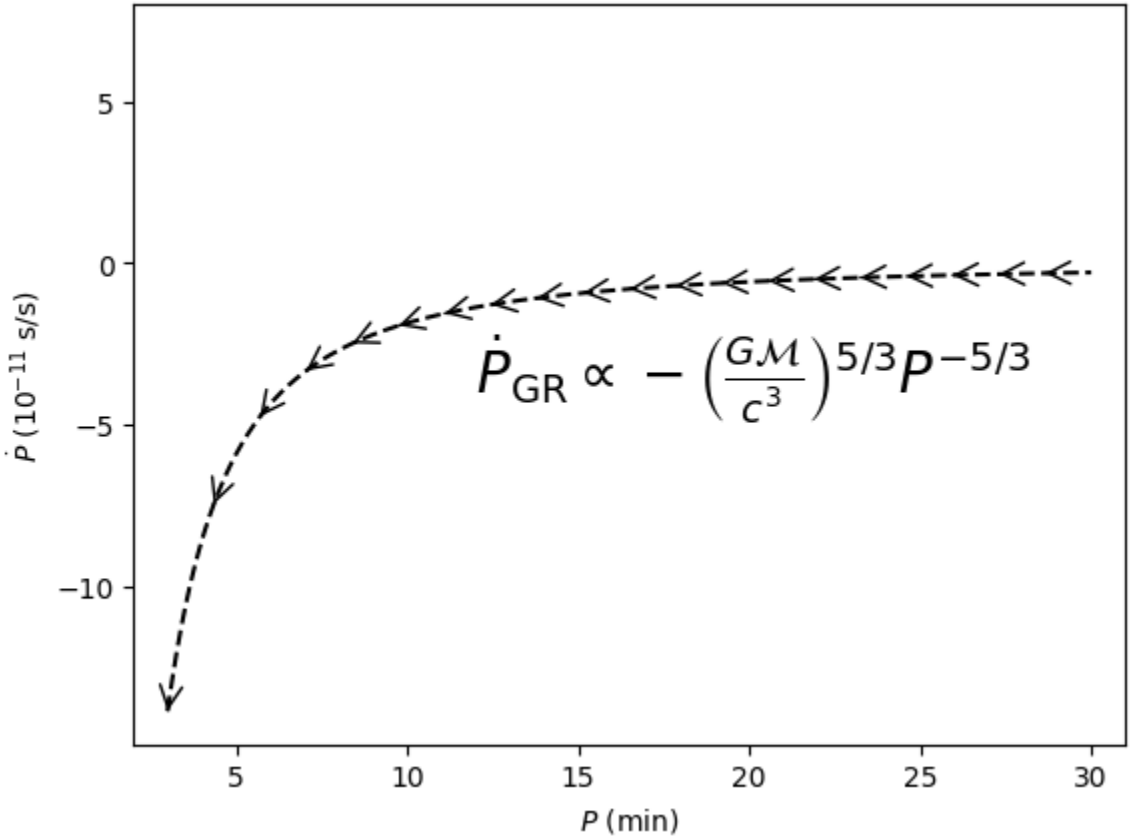


Binary stellar evolution:
the standard picture

LISA will probe the
end stages



Orbital evolution of an ultracompact binary (0.24 $M_\odot$ + 1.0 $M_\odot$)



Period vs. J_{orb} :

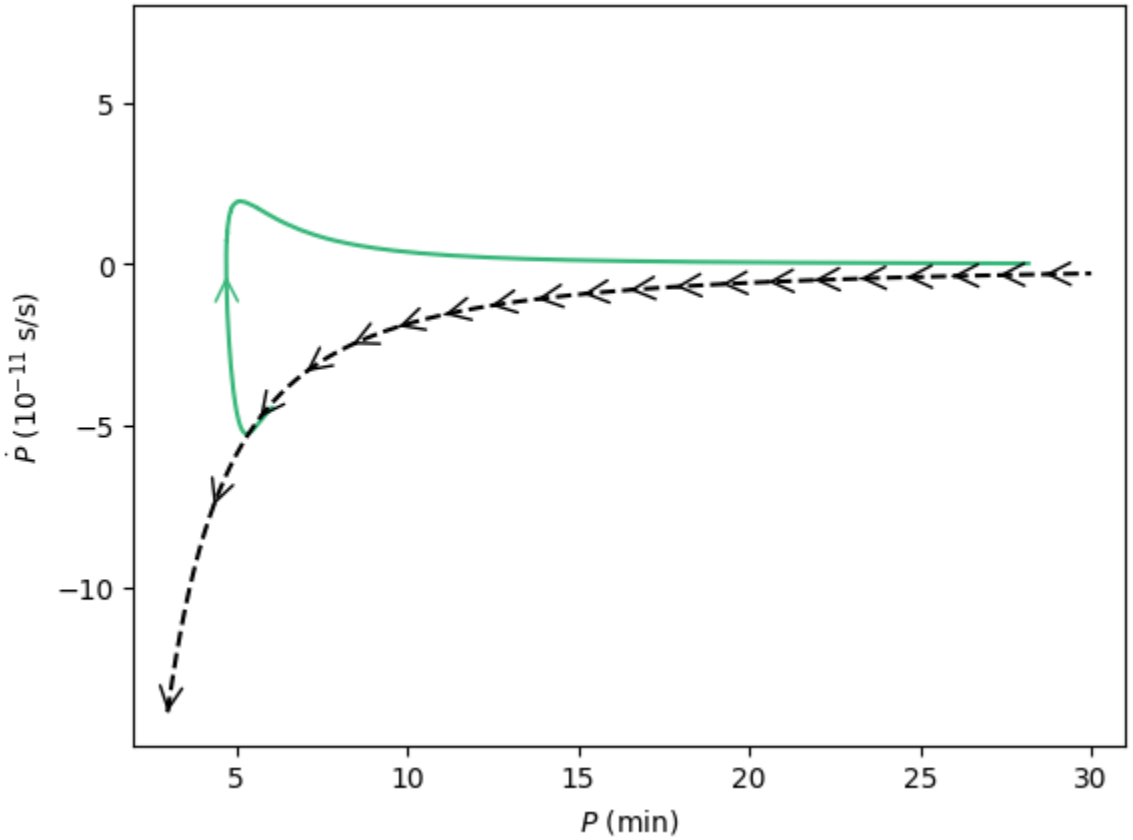
$$P = J^3 (M_1 + M_2)(M_1 M_2)^{-3} \left(\frac{2\pi}{G^2}\right)$$

d lnP/dt:

$$\frac{\dot{P}}{P} = 3\left[\frac{\dot{J}}{J} + \frac{|\dot{M}|}{M_2}(1-q)\right]$$

$q = M_1 / M_2$

Orbital evolution of an ultracompact binary (0.24 $M_\odot$ + 1.0 $M_\odot$)



models from Wong+21

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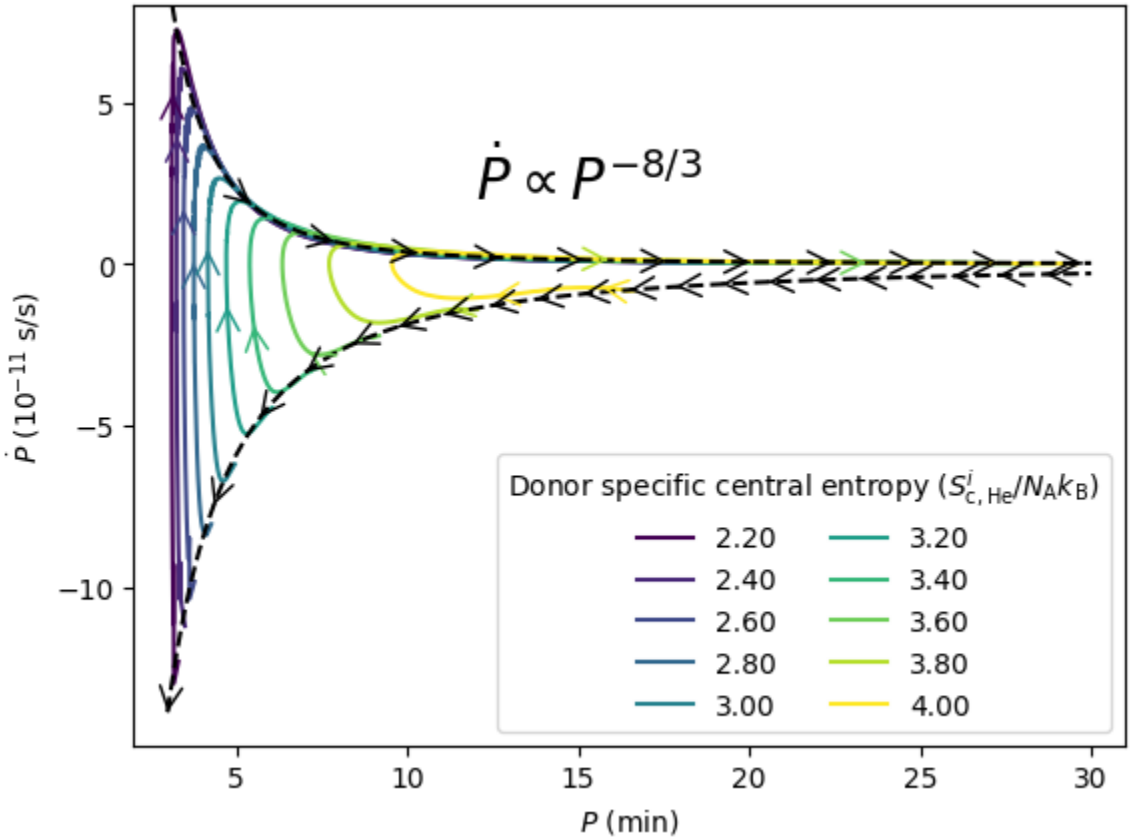

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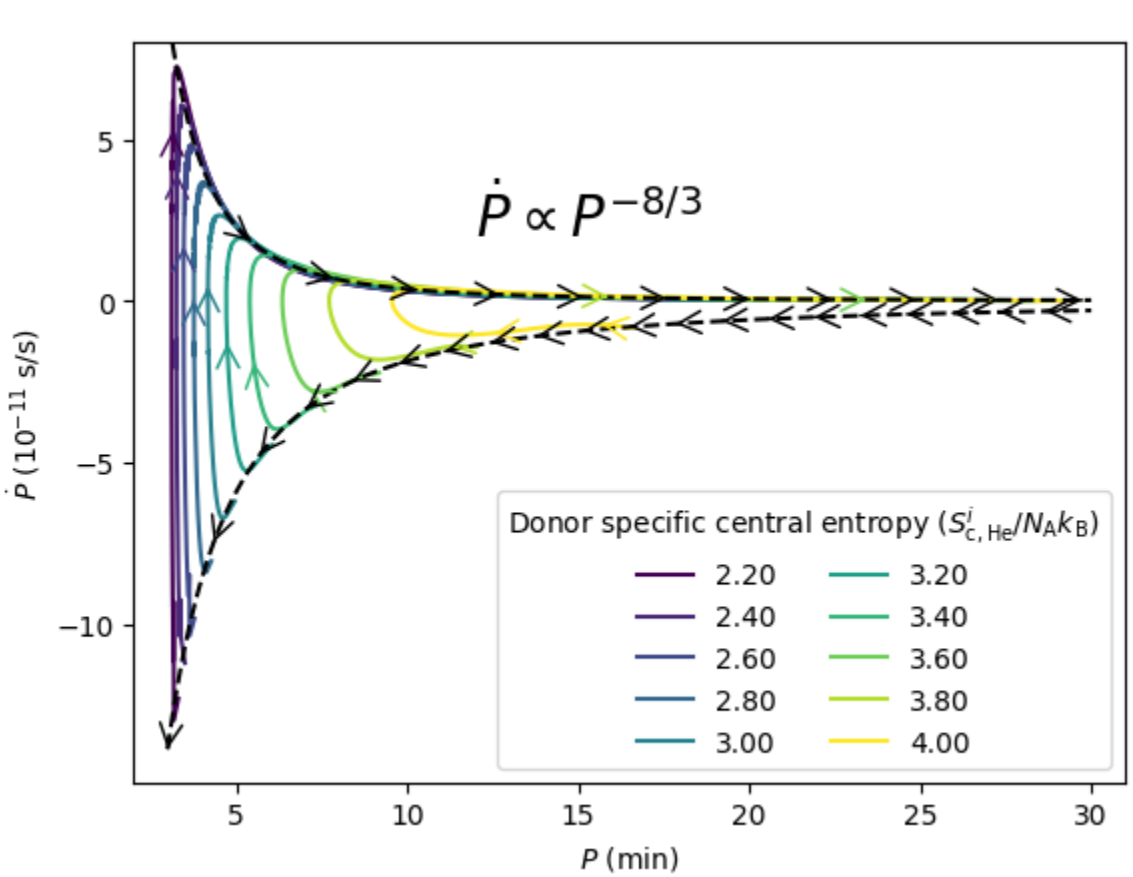
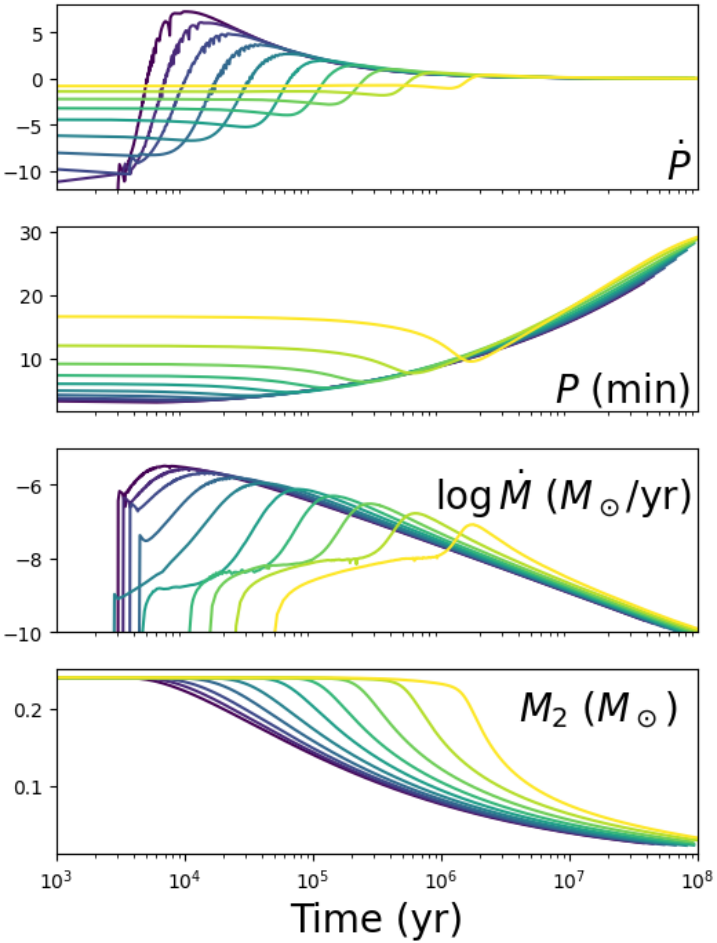


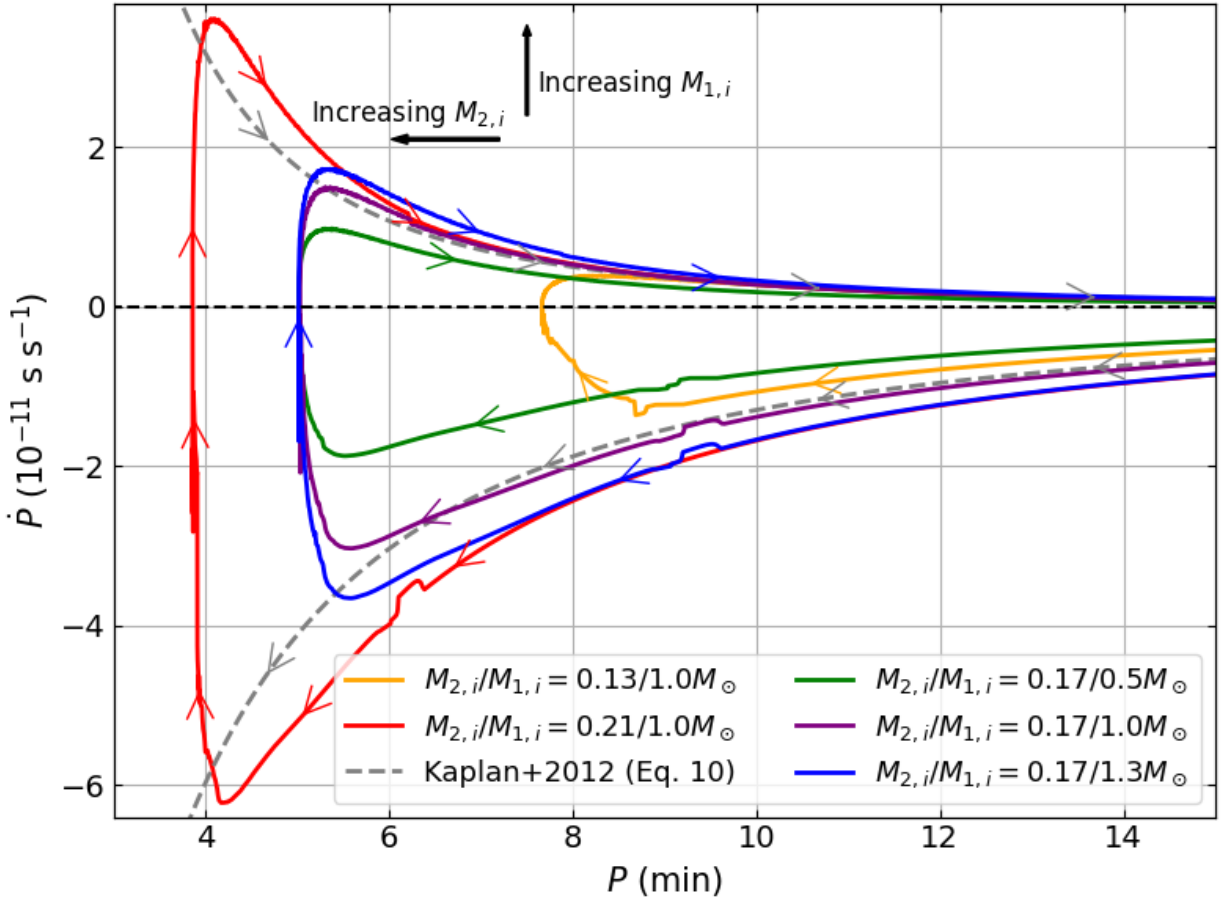


models from Wong+21

Can also vary M_1, M_2,

donor thermal evolution, …

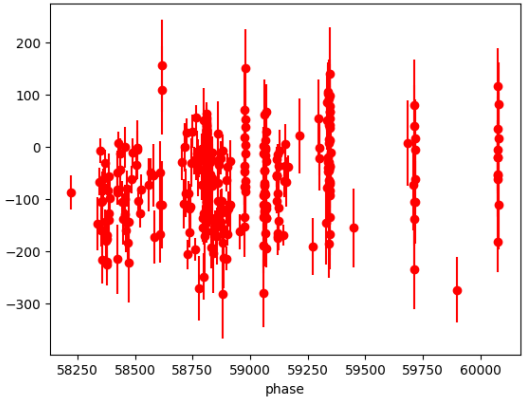
How can we *test* these models and *learn something* about the uncertain physics?



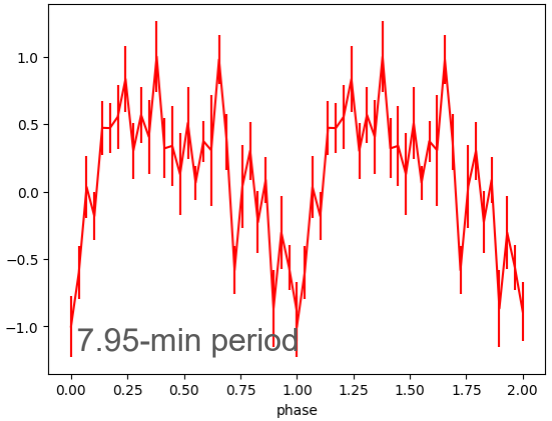
Chakraborty+24

All-sky survey (ZTF)

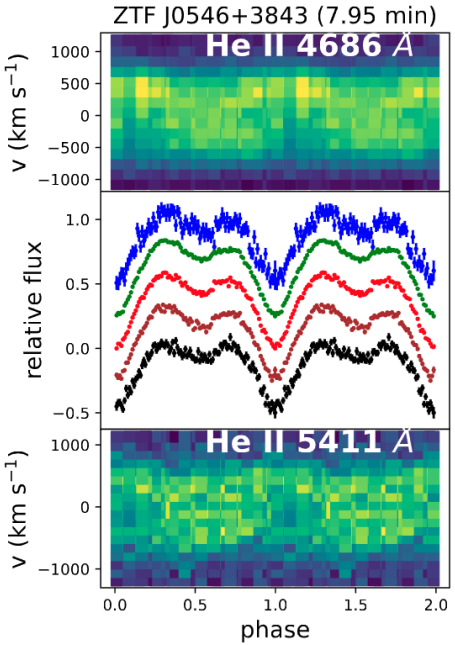
long-baseline photometry

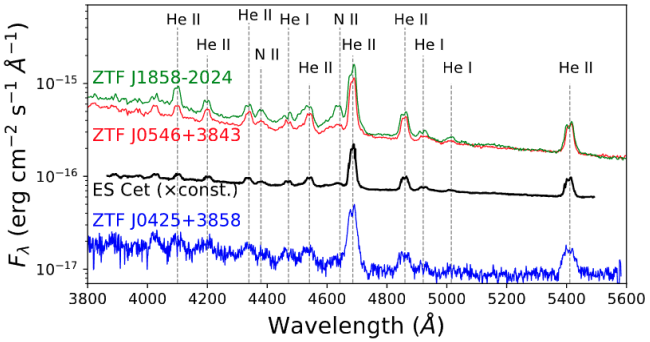


periodicity search
(e.g. Burdge+20)



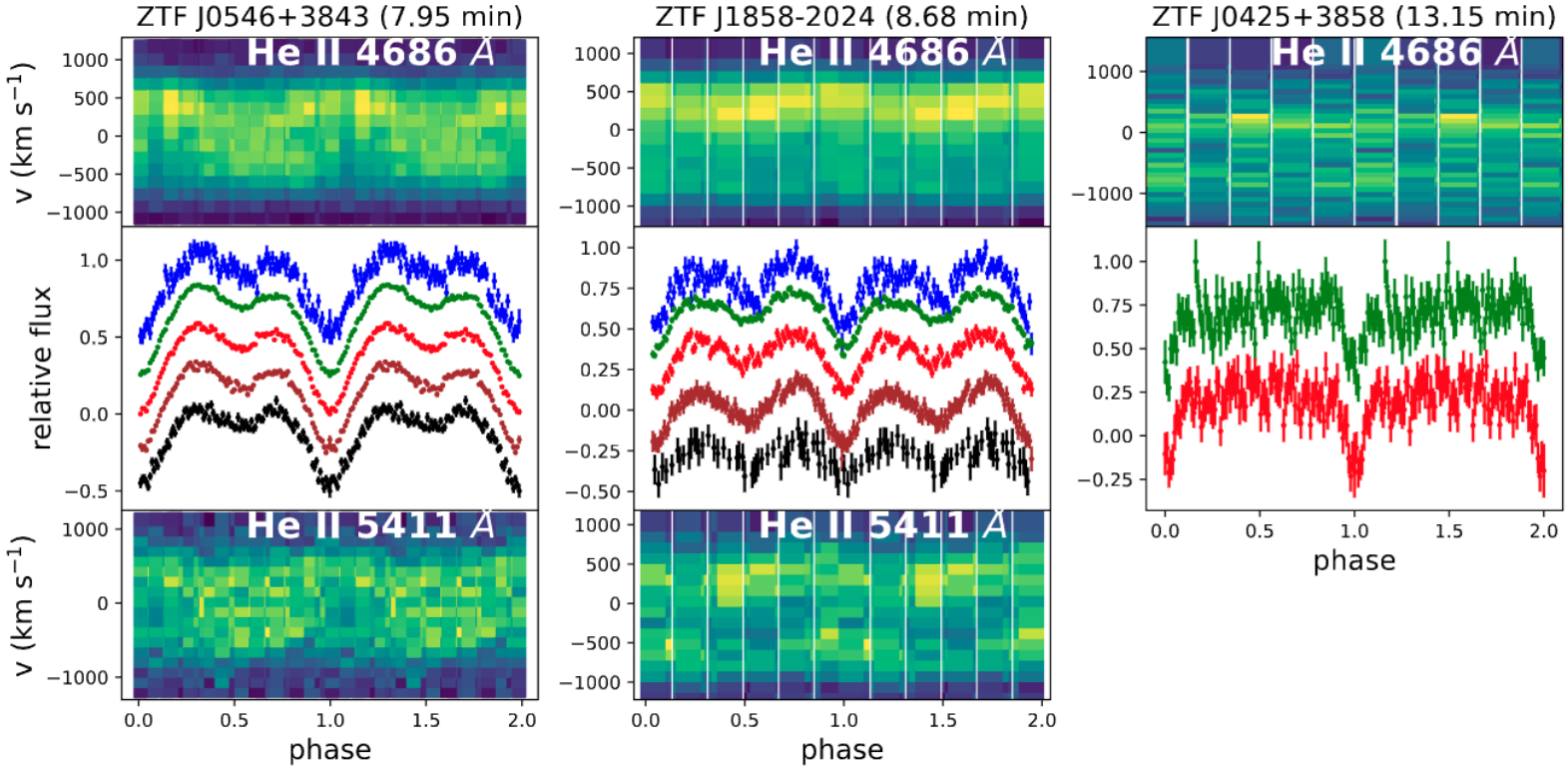
photometric &
spectroscopic
follow-up



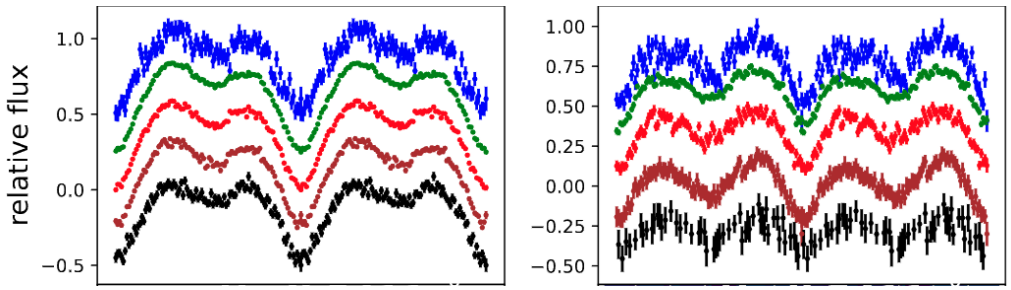


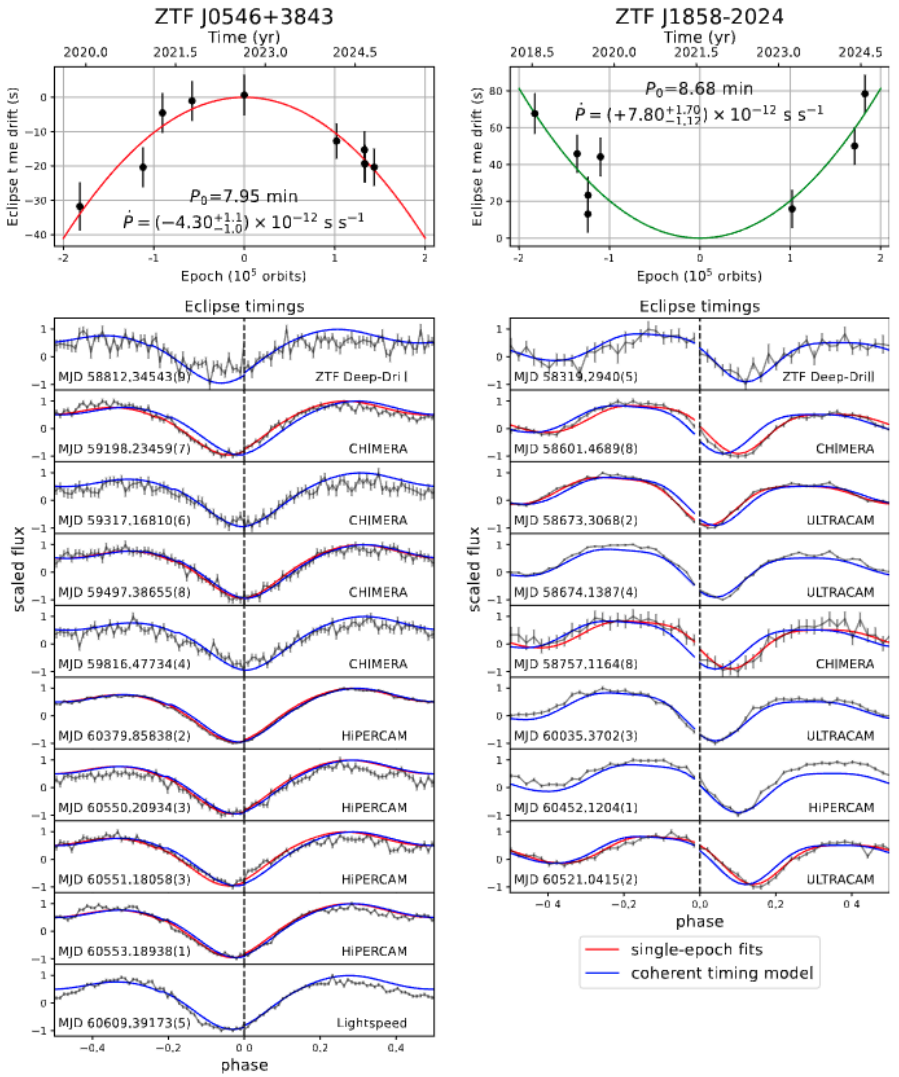
Expanding the ultracompacts: gravitational wave-driven mass transfer in the shortest-period binaries with accretion disks

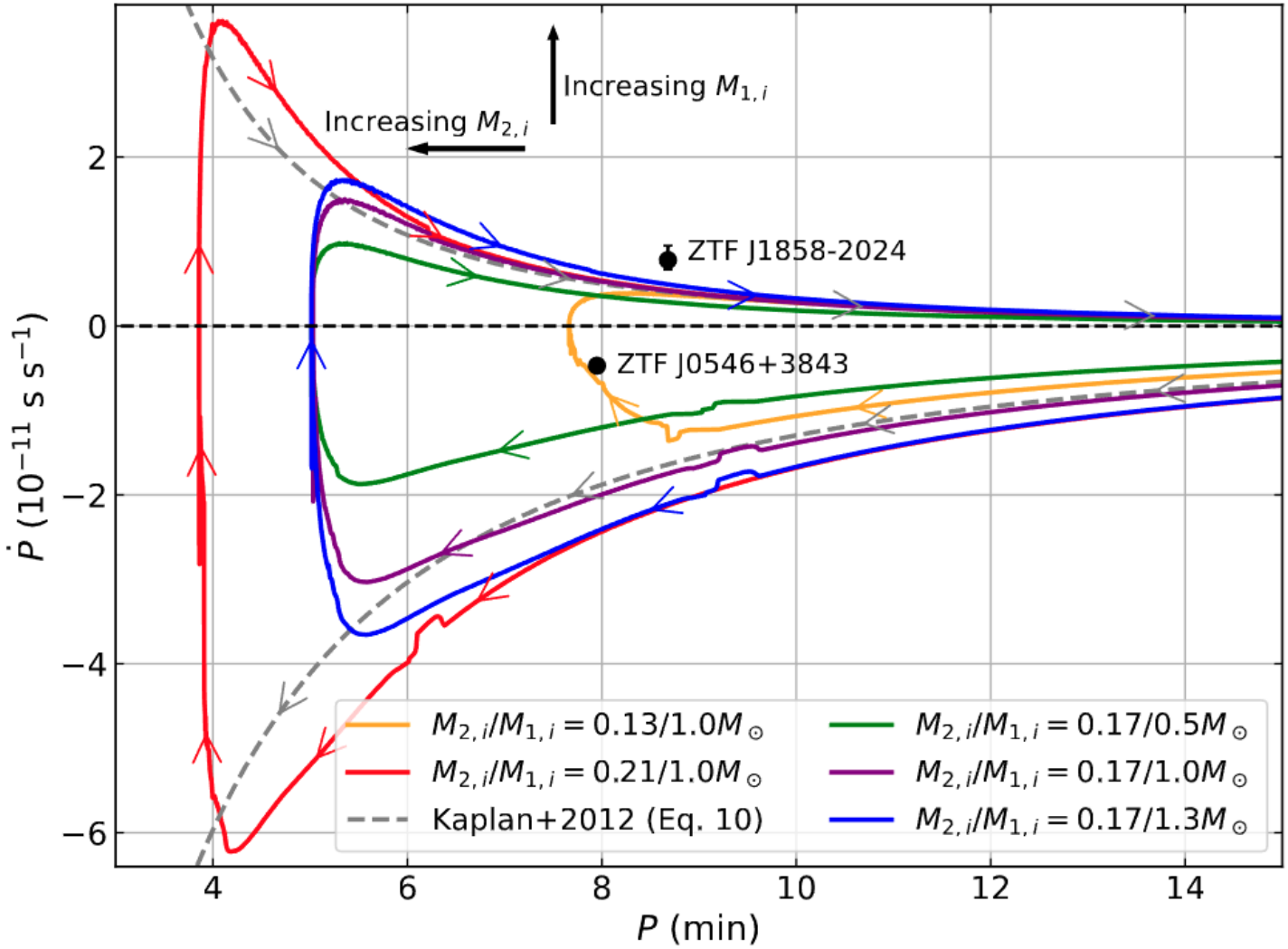
Joheen Chakraborty [1] Kevin B. Burdge [1] Saul A. Rappaport [1] James Munday [2] Hai-Liang Chen [3,4]
Pablo Rodríguez-Gil [5,6] V. S. Dhillon [7,5] Scott A. Hughes [1] Gijs Nelemans [8,9,10] Erin Kara [1]
Eric C. Bellm [11] Alex J. Brown [12] Noel Castro Segura [2] Tracy X. Chen [13] Emma Chickles [1]
Martin J. Dyer [7] Richard Dekany [14] Andrew J. Drake [15] James Garbutt [7] Matthew J. Graham [15]
Matthew J. Green [16] Dan Jarvis [7] Mark R. Kennedy [17] Paul Kerry [7] S. R. Kulkarni [15]
Stuart P. Littlefair [7] Ashish A. Mahabal [15] Frank J. Masci [13] James McCormac [2]
Steven G. Parsons [7] Ingrid Pelisoli [2] Eleanor Pike [7] Thomas A. Prince [15] Reed Riddle [15]
Jan van Roestel [18] Dave Sahman [7] Avery Wold [13] and Tin Long Sunny Wong [19]



Long-term timing (4-6 year baselines)



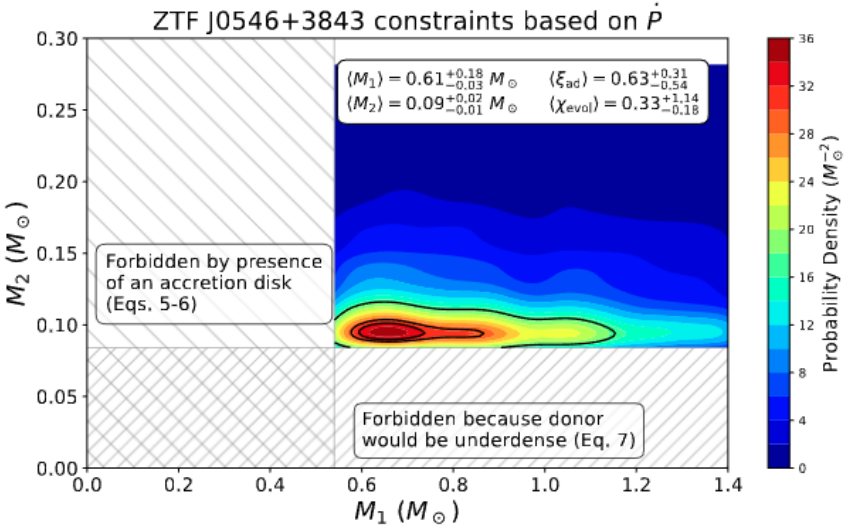


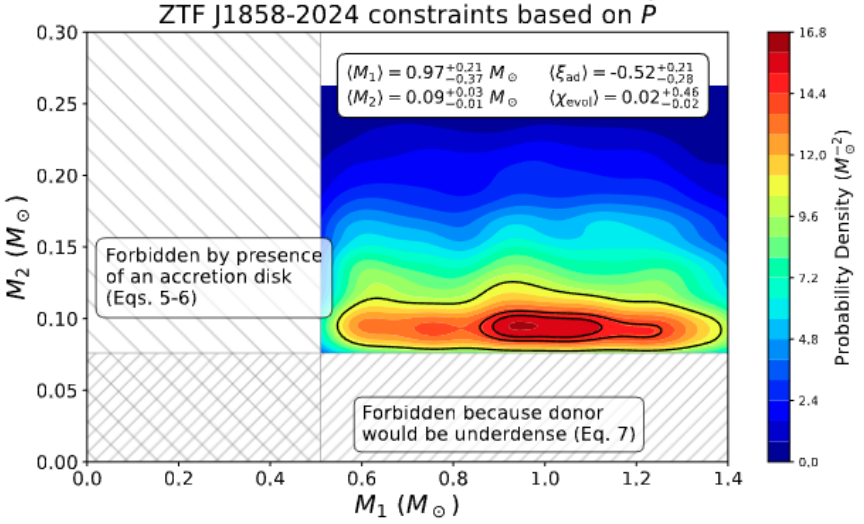

Increasing $M_{1,i}$
Increasing $M_{2,i}$
ZTF J1858-2024
ZTF J0546+3843
$M_{2,i}/M_{1,i} = 0.13/1.0M_\odot$
$M_{2,i}/M_{1,i} = 0.21/1.0M_\odot$
Kaplan+2012 (Eq. 10)
$M_{2,i}/M_{1,i} = 0.17/0.5M_\odot$
$M_{2,i}/M_{1,i} = 0.17/1.0M_\odot$
$M_{2,i}/M_{1,i} = 0.17/1.3M_\odot$
$\dot{P}$ (10^{-11} s s^{-1})
P (min)
2
0
−2
−4
−6
4
6
8
10
12
14

$$\frac{\dot{P}}{P} = 3\left[\frac{\dot{J}}{J} + \frac{|\dot{M}|}{M_2}(1-q)\right]$$

Write in terms of stellar evolution parameters ($\xi_{\rm ad}$, $\chi_{\rm evol}$)

$$\left(\frac{\dot{P}}{P}\right)_{\rm eq} = 3\left(\frac{\dot{J}}{J}\right)_{\rm GW}\left[\frac{\xi_{\rm ad} + \chi_{\rm evol}(1-q) - 1/3}{\xi_{\rm ad} + 5/3 - 2q}\right]$$



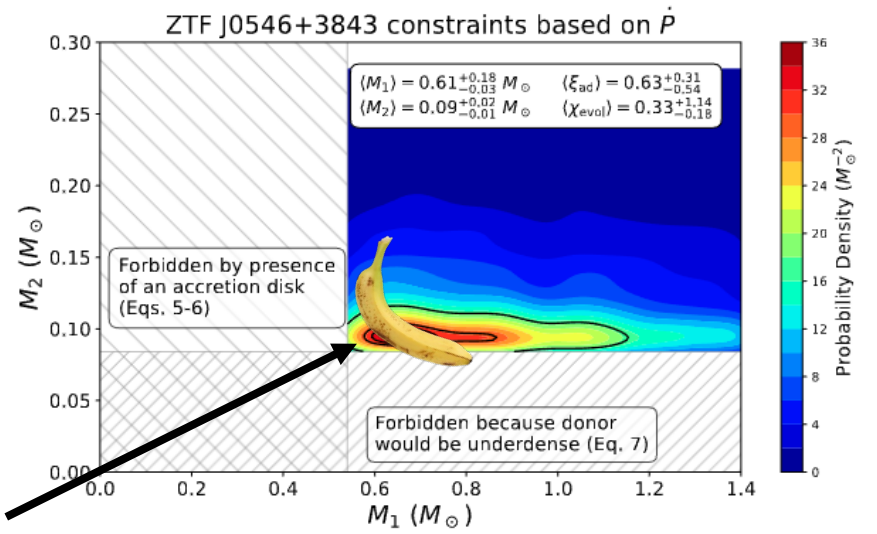


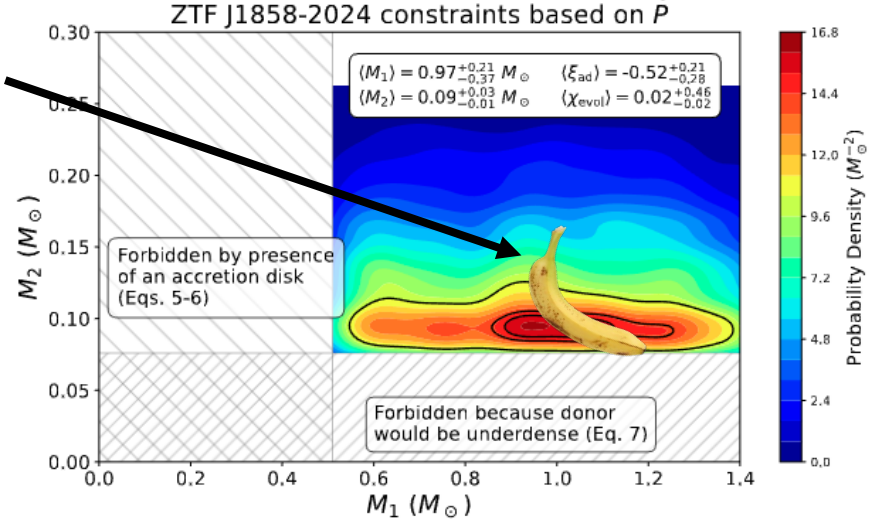
$$\frac{\dot{P}}{P} = 3\left[\frac{\dot{J}}{J} + \frac{|\dot{M}|}{M_2}(1-q)\right]$$

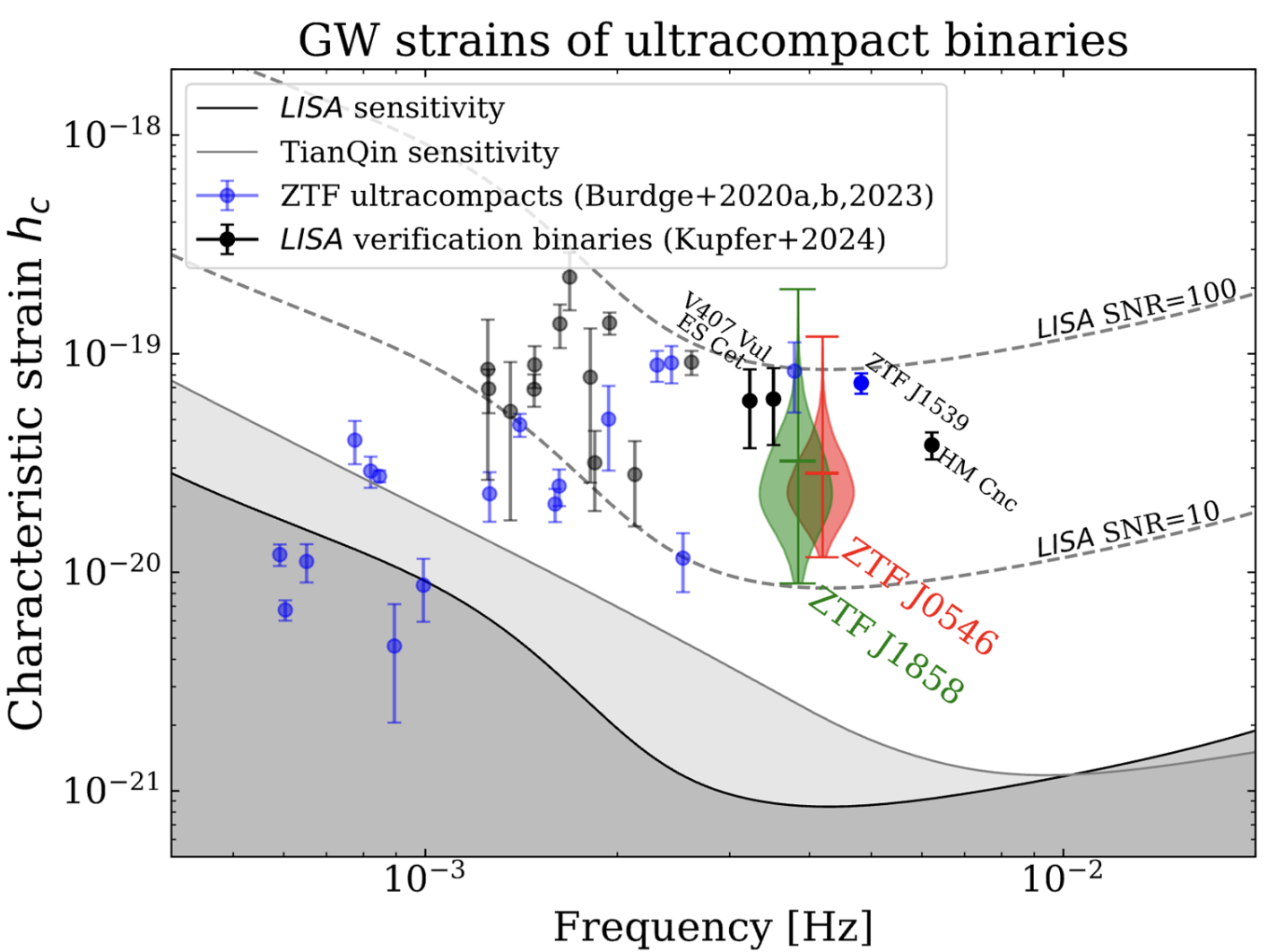
Write in terms of stellar evolution parameters ($\xi_{\rm ad}$, $\chi_{\rm evol}$)

Complementary to *LISA* measurements!

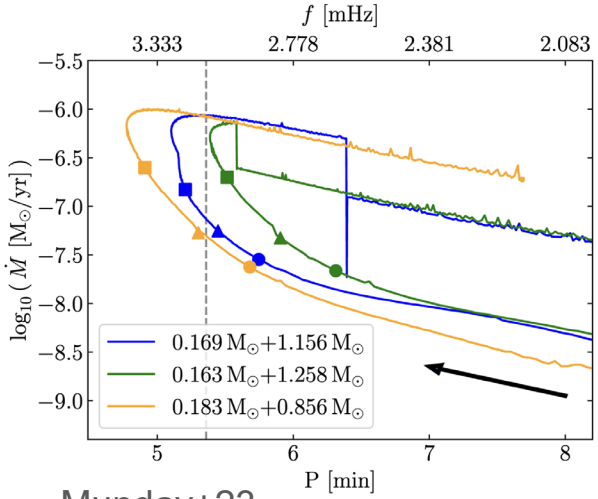
$$\left(\frac{\dot{P}}{P}\right)_{\rm eq} = 3\left(\frac{\dot{J}}{J}\right)_{\rm GW}\left[\frac{\xi_{\rm ad} + \chi_{\rm evol}(1-q) - 1/3}{\xi_{\rm ad} + 5/3 - 2q}\right]$$





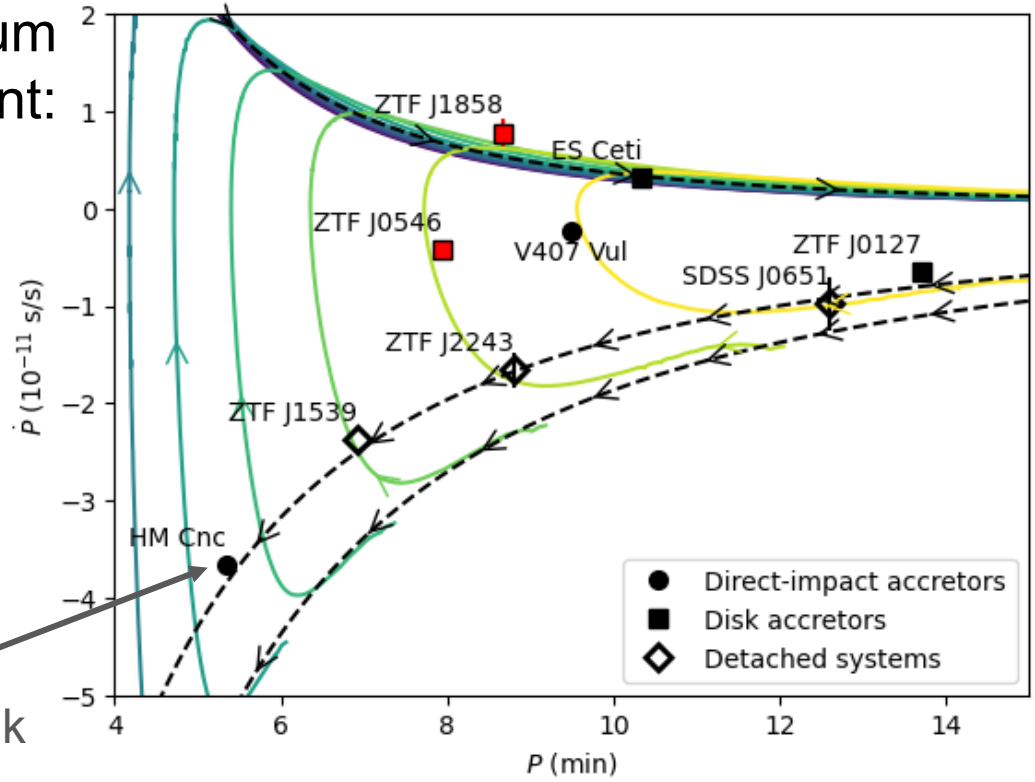

GW strains of ultracompact binaries
LISA sensitivity
TianQin sensitivity
ZTF ultracompacts (Burdge+2020a,b,2023)
LISA verification binaries (Kupfer+2024)
LISA SNR=100
LISA SNR=10
V407 Vul
ES Cet
ZTF J1539
HM Cnc
ZTF J0546
ZTF J1858
Characteristic strain h_c
Frequency [Hz]
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-3}
10^{-2}

Every system near period minimum with a direct *P*-dot measurement:



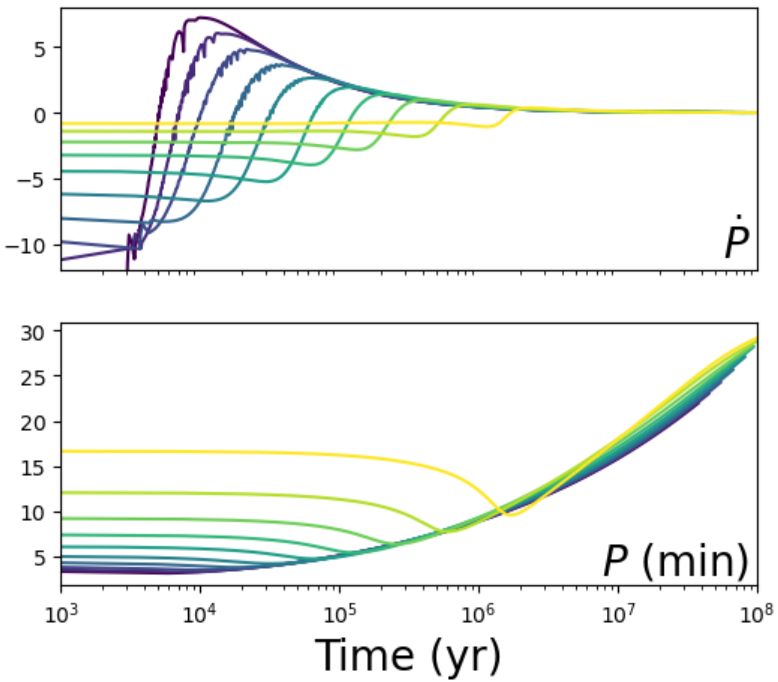
Munday+23

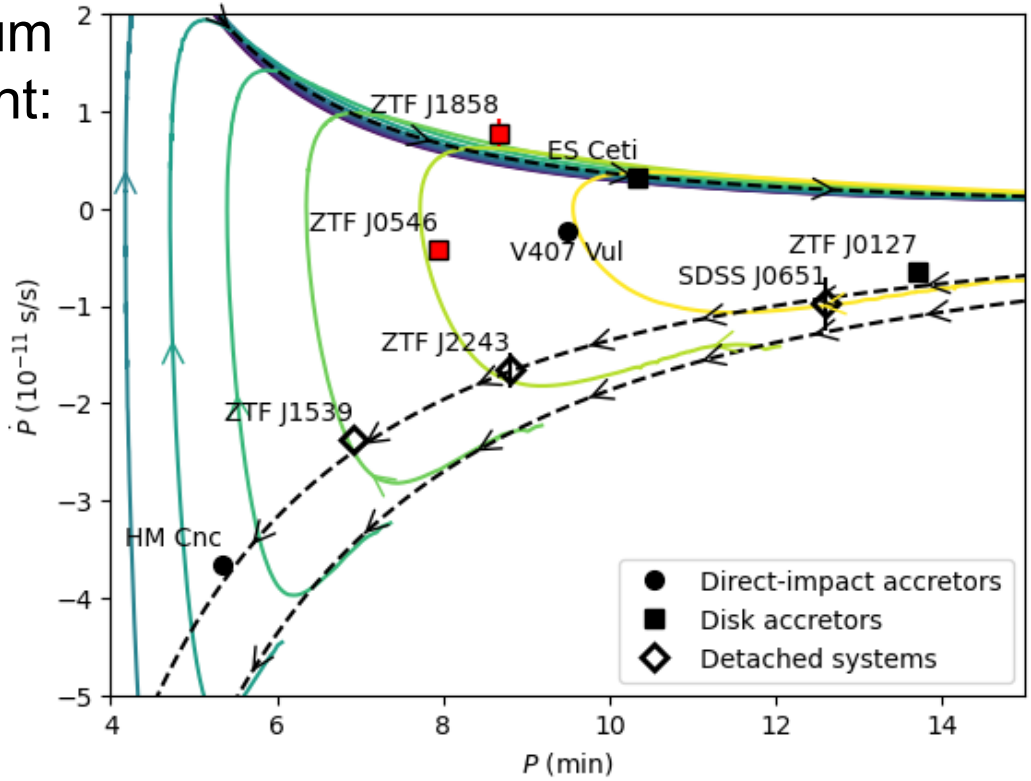
James' talk



*tracks are illustrative, NOT fits

Every system near period minimum with a direct *P*-dot measurement:



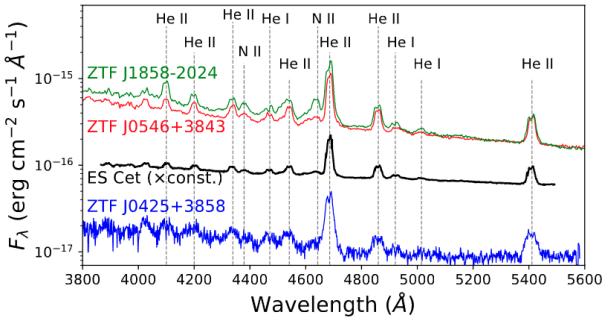


$$\mathcal{N}_{\rm out/in} \equiv \left| \frac{\dot{P}_{\rm in}}{\dot{P}_{\rm out}} \right| \approx 4(P/10\,{\rm min})(M_{\rm He}/0.15\,M_\odot)$$

(Kaplan+12)

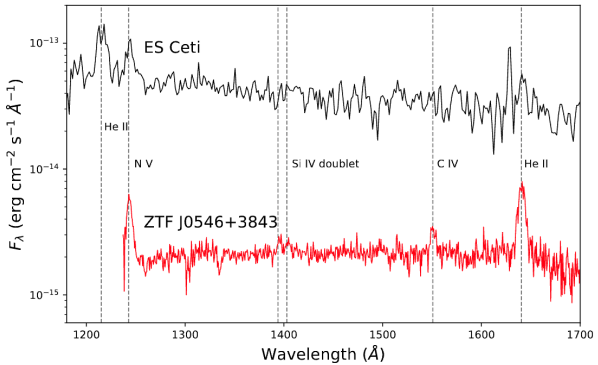
… the observed *P*-dot distribution is perhaps odd, but it's still early

Optical



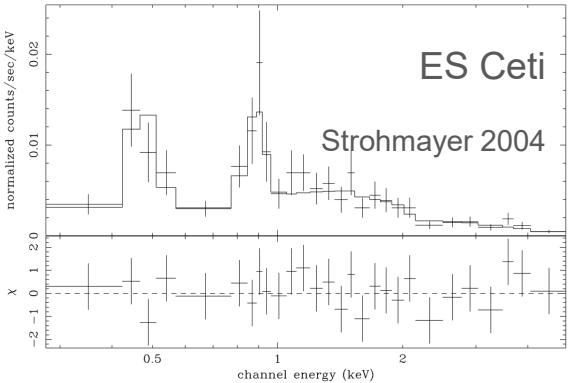
+

UV

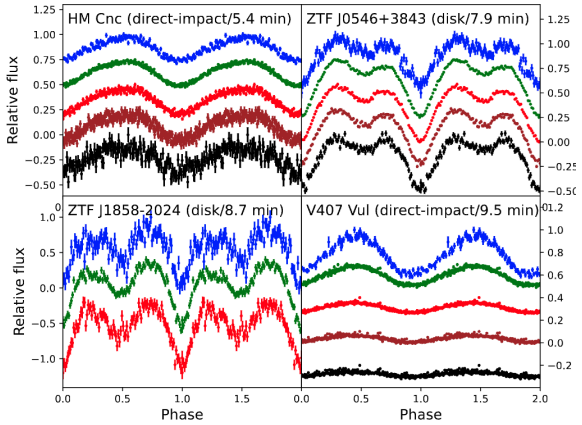


+

X-ray

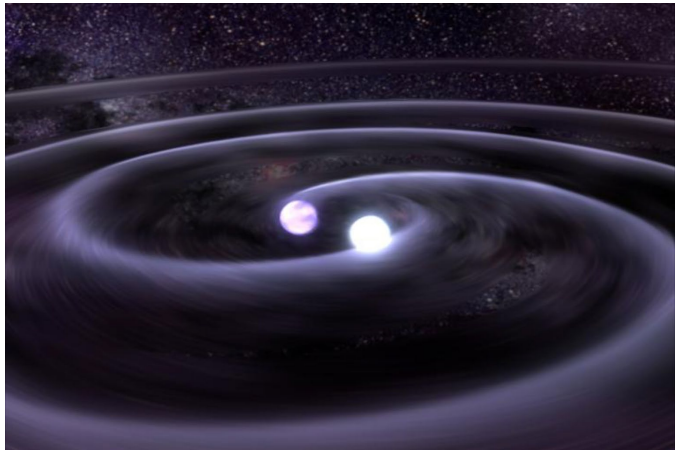


Spectroscopy + photometry



+ GW signal

Many simultaneous data channels will allow for new, precise mapping of these systems and their accretion disks!



Ultracompact binaries

Evolutionary models

Observational tests

rates/population forecasting
individual high-SNR sources

Ultracompact binaries

Evolutionary models
Observational tests

LISA observations

Complementary GW signal

rates/population forecasting
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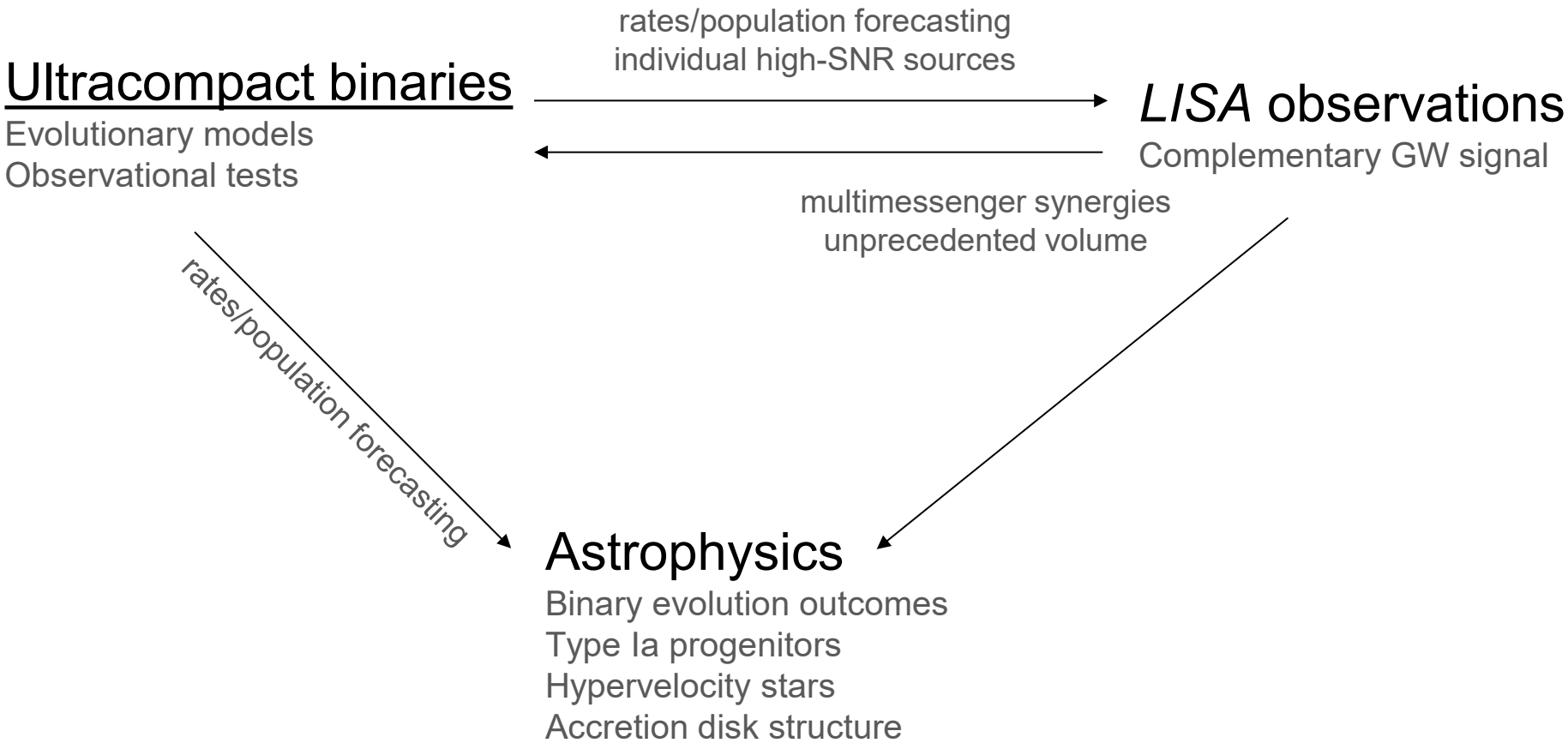
rates/population forecasting

Astrophysics

Binary evolution outcomes
Type Ia progenitors
Hypervelocity stars
Accretion disk structure


rates/population forecasting
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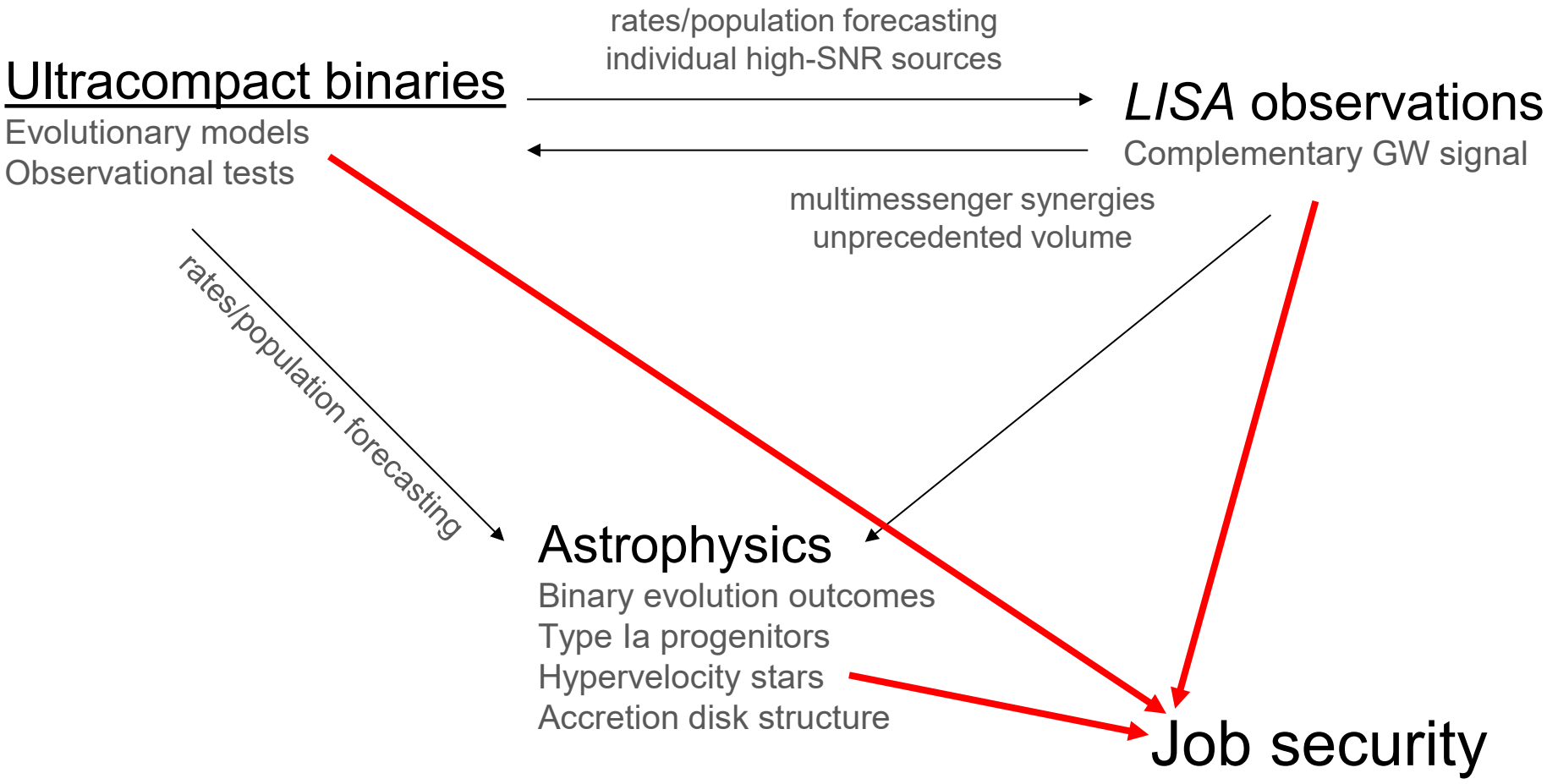
rates/population forecasting
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multimessenger synergies
unprecedented volume
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Astrophysics
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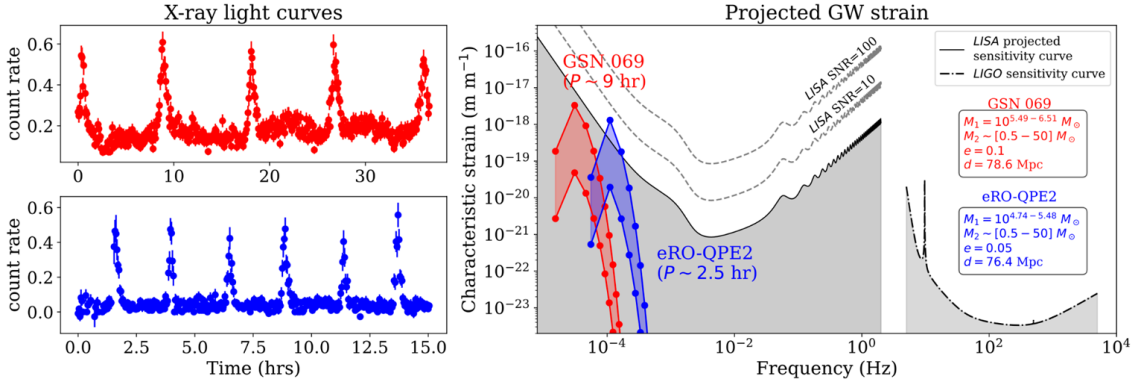
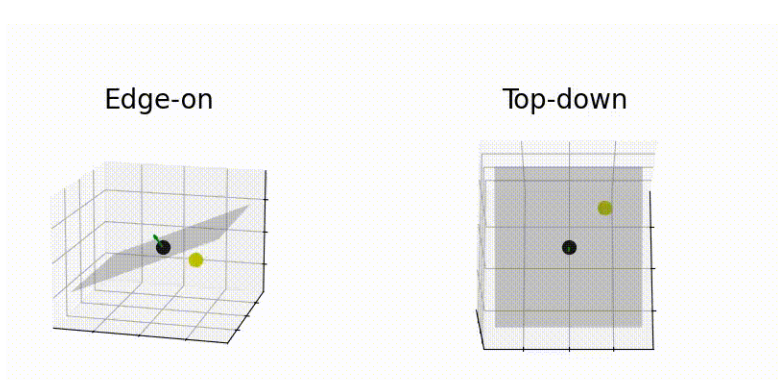
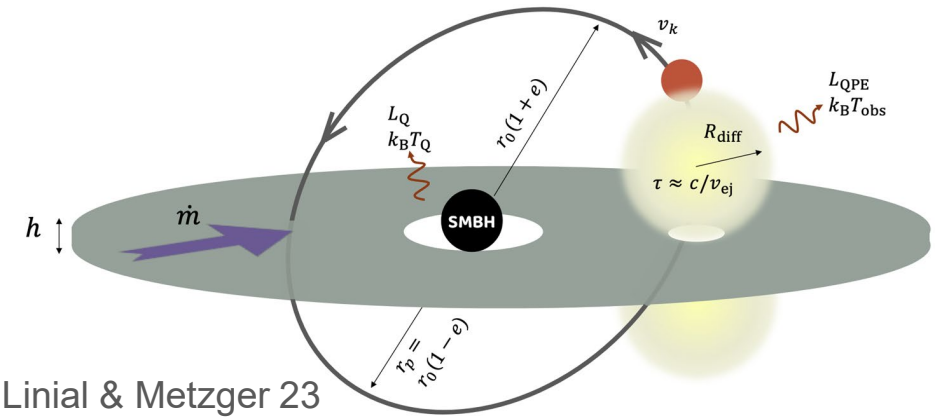
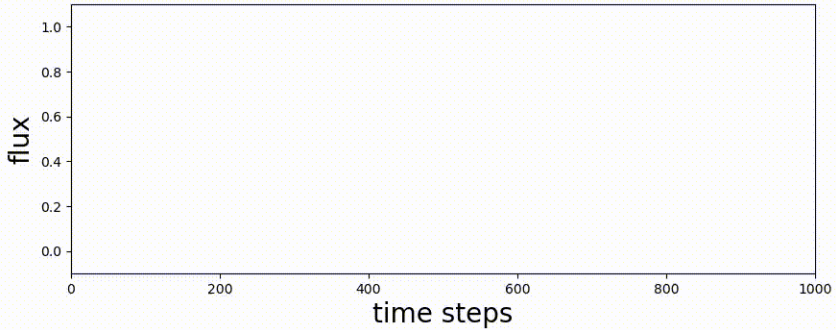
Hypervelocity stars
Accretion disk structure
Job security

My other hobby in *LISA* science: quasi-periodic eruptions (X-ray counterparts to EMRIs?)



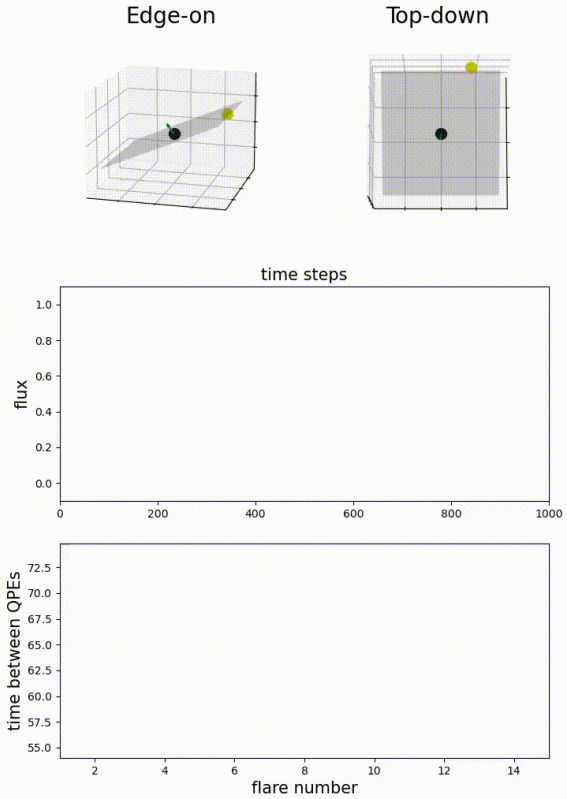






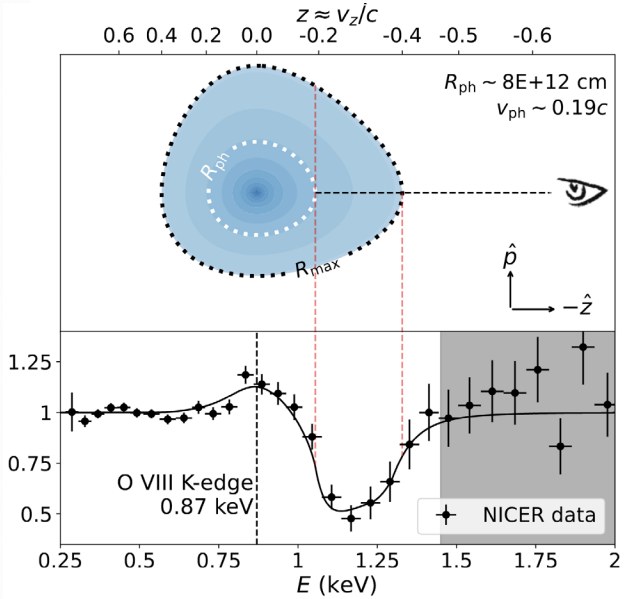
Linial & Metzger 23

QPE timing: SMBH dynamical probes down to ~100 R_g



Chakraborty+24a

QPE spectra: probes of energy dissipation ⇒ orbital decay



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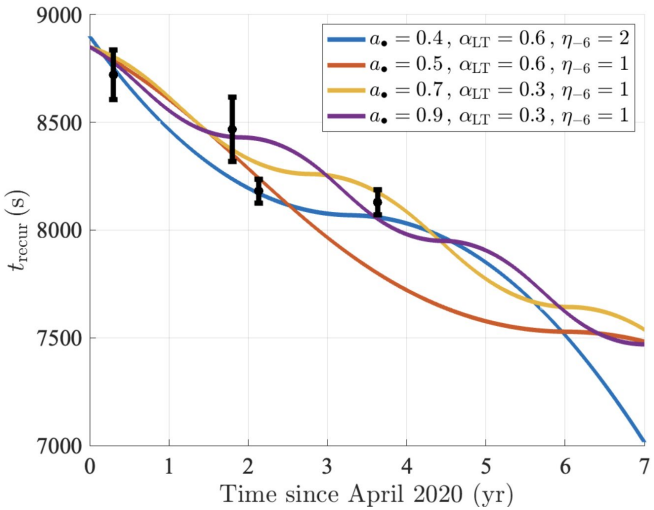
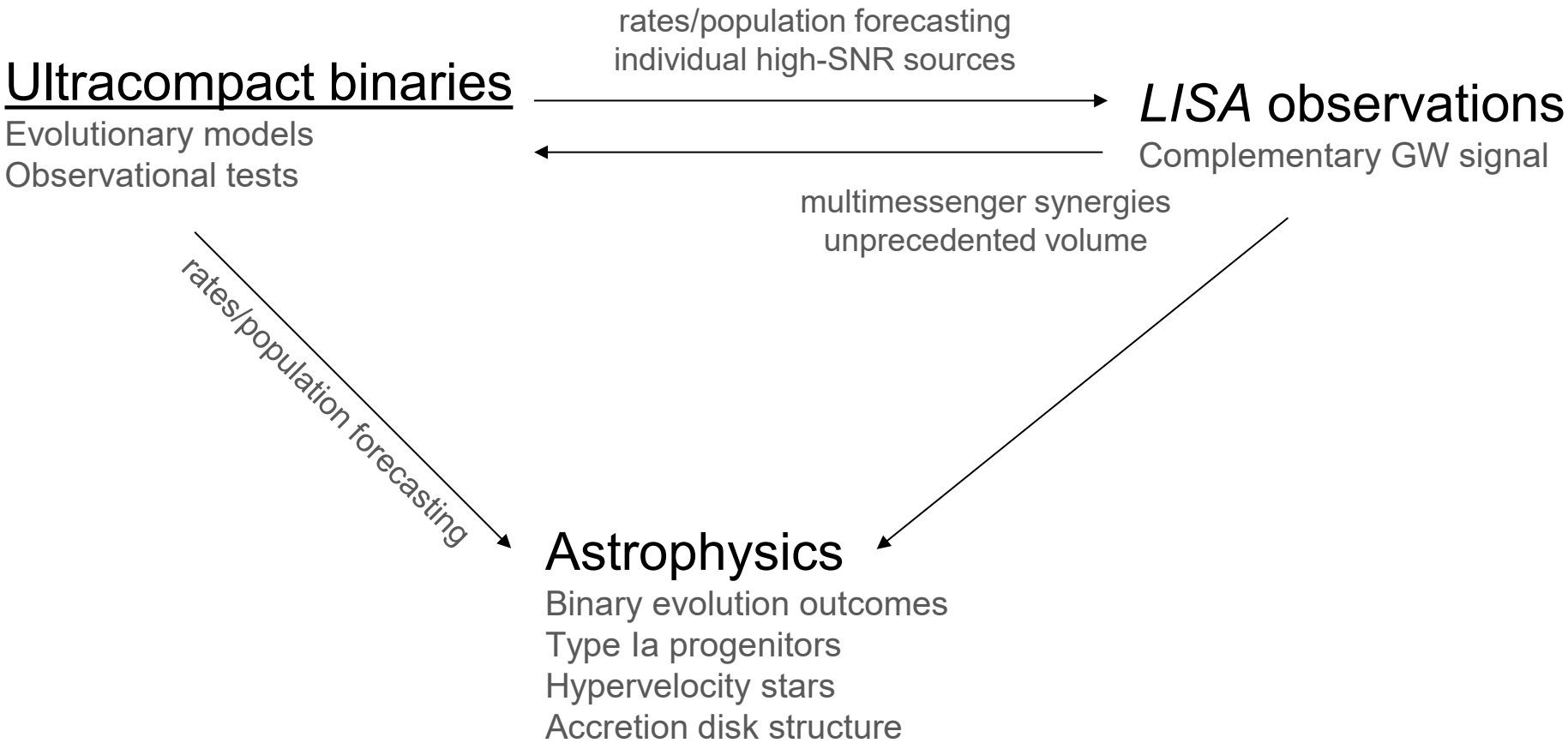
Preliminary observations of **orbital decay** driven by GWs + gas dissipation



Arcodia+24c (incl. Chakraborty)



Thanks for listening! Reach me at joheen@mit..edu

Chakraborty *et al.*, 2024 – arXiv:2411.12796 (Dec. 2024)